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Steer By Wire In Agricultural Tractors

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Abstract— Agricultural tractors are off road equipments used in the worst terrains available in earth. They are exposed to high friction surfaces – farm fields. The front axle steering forces vary in a very large scale with respect to loads and coefficient of friction of the farmland. The popular technologies available in tractors are manual steering system using mechanical linkages and power steering system using hydro static steering system using hydraulic power pack. The former one is a fixed ratio system with high steering effort. The later one is a highly effortless system but consumes a good amount of engines energy thereby affecting the mileage. Steer by wire systems provide variable ratio steering and consumes only very less amount of energy to work.

Index Terms— Ackermann geometry, Front axle, Self alignment,Steering effort, Turning circle, Tractor.

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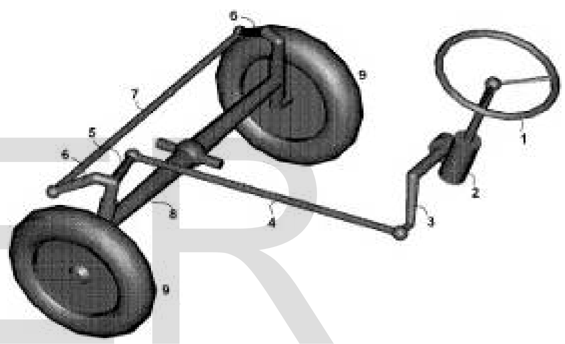
1 INTRODUCTION

AN integral design change to achieving these objectives was switching from a hydraulic steering system to a steer-by-wire (electronic) steering system. Incorporating an electronic system would eliminate the many mechanical parts inherent to a typical hydraulic steering system, thereby reducing the overall weight of the tractor and automatically increasing fuel efficiency. This design change would also improve product reliability simply by eliminating the number of parts potentially subject to failure. Fewer mechanical parts also meant a significant reduction in manufacturing costs. These long-term benefits overcame any short-term costs required to develop the electronic steering.

There has been a general trend away from hydraulics in other applications as well. Many manufacturers are looking to cut back or eliminate the use of hydraulics, so it is becoming much harder to find spare capacity on a hydraulic pump for the steering system. If spare capacity is not available then it becomes necessary to add a hydraulic system dedicated to steering which substantially raises the cost of this approach. Electronic steer-by-wire systems, on the other hand, are completely self-contained and do not require external pumps or hoses. This means that they are usually considerably less expensive than hydraulic steering when the cost of the pump, valve, hoses and fittings are taken into account.

2 TRACTOR STEERING SYSTEMS

Tractor steering systems are of two types in the major popularity – manual steering system and hydro static steering system. Shown in the above picture is a manual steering system used in 2 wheel drive tractors. It consist of 1.steering wheel, 2.steering gear box ,3. Drop arm, 4. Draglink ,5. Spindle arm , 6. Steering arm ,7. Tierod , 8. Front axle beam, 9. Tyre assy.



3 STEER-BY-WIRE IN TRACTOR

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4 LEGAL ASPECTS OF STEER-BY-WIRE SYSTEM

- Mechanical steering systems are considered safe, whereas electronically controlled systems may fail without previously displaying signs of error and are therefore considered less safe. For this reason specific directives will apply to the development of steer-by-wire. The Steer-by-Wire Working Group evaluates standards and legal aspects for the implementation of steer-by-wire systems and gives guidance on how to deal with these issues.
- For motor vehicles for carriage of passengers, goods and their trailers, Framework Directive 2007/46/EC applies for type approval. Among others it lists for the steering effort the Directive UNECE R79. The current ECE R79 in Revision 2 now covers the possibility of full steer-by-wire systems without mechanical backup.
- For Agricultural or Forestry Tractors, especially for faster tractors above 40km/h, directive 70/311/EEC may be applied. This directive, and the more general 75/321/EEC do not cover full steer-by-wire systems, but the latest UN ECE regulations may be applied to some systems. In particular, regulation UN ECE R79 R2 may be applied, allowing full steer-by-wire systems.
- For mobile machinery there exists no separate European Framework Directive. These vehicles are typically nationally type approved for on-road use. Many countries use ECE R79 R2, 70/311/ECC or 75/31/ECC concerning steering as possible basis for national approval. Therefore an independent test report on the steering system on that basis usually considerably simplifies the national type approvals, especially for those countries that also accept EC Directives and UN ECE Regulations as an alternative to the national type approval regulations.
- Besides regulatory requirements from the type approval procedure, the manufacturer of steer-by-wire systems also needs to consider liability aspects including the electronic control and communication system. Standards such as IEC 61508 are used to avoid and control any systematic design faults and to deal with random hardware faults.

3.1 COMPONENTS OF STEER-BY-WIRE

1. Steering wheel
2. Torque Sensing Device
3. Position Measur ing Device
4. Self-locking/one-way Mechanism/Gear
5. Motor (a)
6. Processor
7. Motor (b)
8. Steering Gear
9. Position Measuring Device
10. Torque Measuring Device
11. Tie rods
12. Steered wheels

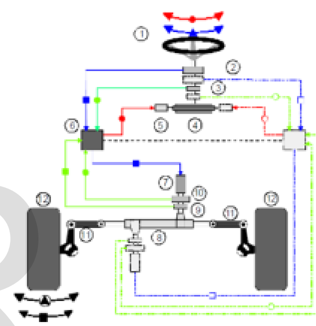

Fig. Steer by wire working

3.2 WORKING PRINCIPLE

The system basically consists of two separate systems;

1. a control system that enables the driver to control the steerable wheels of the tractor
2. a feedback system that allows the driver to sense the reaction of the steerable wheels in the steering wheel.

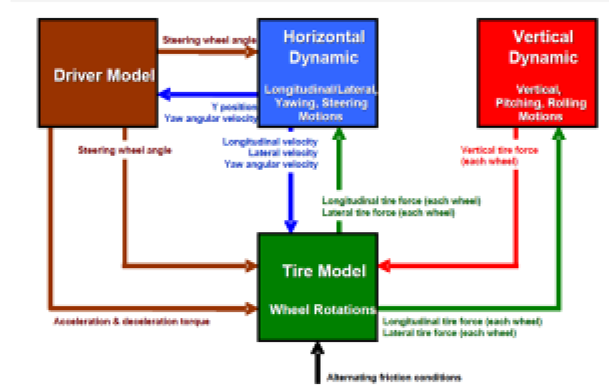

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Fig. Steer by wire block diagram

The torque applied by the driver on the steering wheel is measured by a torque measuring device and transmitted to a processing unit. The processing unit controls a motor to produce a torque corresponding to the torque applied

by the driver on the steering wheel. If the torque applied by the motor (b) to the steering gear is sufficient to overcome friction and road forces, the wheels will begin to move. The steering gear can be a traditional rack-and-pinion drive

connected to the steered wheels by tie rods. If external forces acting on the steered wheels exceed the force applied by the tie rods from the torque provided by motor (b) through the steering gear, the wheels will move as well.

4 ACKERMANN GEOMETRY

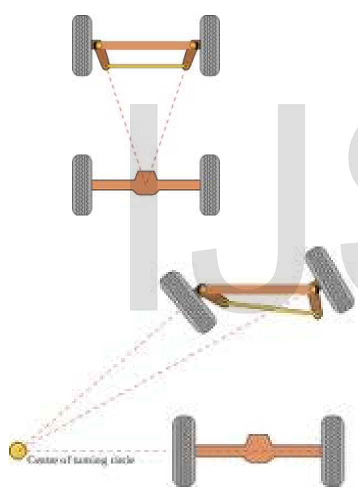

Fig. Ackermann geometry

COT (IWA) – COT (OWA) = CC/WB

IWA – Inner Wheel Angle

OWA – Outer Wheel Angle

WB – Wheel Base

CC – Center to center of pivot.

INNER WHEEL ANGLE = 48 DEG

OUTER WHEEL ANGLE = 33DEG

TURNING RADIUS = 2800MM

5 STEERING EFFORT

Measured steering effort in the manual steering tractor has a maximum value of 10 Kg when vehicle is at stand still condition. As per regulatory requirements, the maximum steering effort with a malfunctioning steering should not exceed 60 Kg. The objective of this project is to achieve the same specifications as the above manual steering and excel wherever there is possibility.

6 CONVENTIONAL MANUAL STEERING TRACTOR SPECIFICATION

FRONT TRACK	1320MM	52INCH
REAR TRACK	1340MM	52.75INCH
WHEEL BASE	1760	MM
POWER	37.5PS/27.6KW	AT2000RPM
TORQUE	15.5	KGM
CC	2400	
RPM	2000	2200
STEERING	19.6	1
STG WHEEL DIA	450	MM
LOCK TO LOCK	4.2 TURNS	
STEERING ANGLE	51DEG	
FRONT AXLE	SWEPT FIXED	
CAMBER	3.5	
CASTOR	2	
TOE IN	2 - 4 MM	
TYRE		
FRONT	6.00 X 16	
REAR	12.4 X28	
TURNING CIRCLE RADIUS		
WITH BRAKES	2800	MM
WITHOUT BRAKES	3125	MM
WEIGHT		
FRONT AXLE WEIGHT	700	KG
REARAXLE WEIGHT	1000	KG
APPLICATION		
11TINE TILLER		
FULL CAGE WHEEL		
HALF CAGE WHEEL		
ALTERNATOR		
10 TON TIPPING TRAILER		

Table MF 1035 tractor specification

7 STEER-BY-WIRE SYSTEM ARCHITECTURE

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Figure shows a schematic diagram of a vehicle steer by-wire system. The steer-by-wire system includes a steering wheel mechanism (controlled plant) and a road wheel mechanism (controlled plant). An electronic control module (steer-by-wire controller) controls the steering wheel mechanism and the road wheel mechanism in coordinated fashion. The steer-by-wire controller effectively links the steering wheel and road wheel mechanisms by wire through control signals.

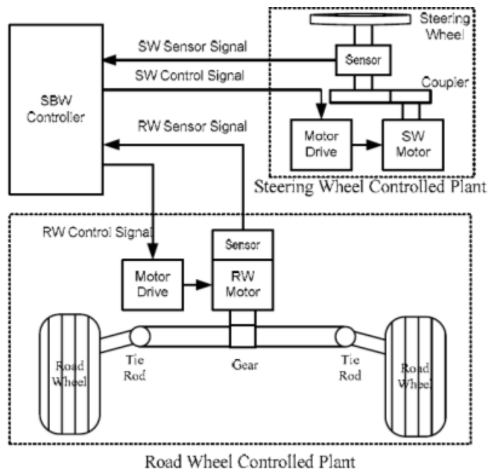

Fig. Steer By Wire Layout

As shown in above Figure, the conventional hydraulic steering assembly has been replaced by an electric motor actuator to drive the road wheels in the road wheel mechanism. Road wheels are connected to a rack and pinion mechanism by tie rods. An angle sensor mounted in the motor or the rack and pinion mechanism is used to sense the road wheel angles. The steer-by-wire controller receives road wheel angle signals and produces a control signal to the permanent magnet brushless Direct Current (DC) motor through its electricdrive. The primary goal for controlling the road wheel mechanism is to keep the road wheel tracking for the reference road wheel angle. The reference road wheel angle signal comes from the steering wheel assembly and changes according to the vehicle driver's intent and the vehicle dynamics requirements. This system consisting of the road wheel mechanism and its control is referred as the road wheel control subsystem. The steering wheel mechanism consists of a steering wheel mounted to a steering shaft, a steering wheel angle sensor mounted to the steering shaft for sensing a steering wheel angle, a DC electric motor and its drive, and a belt and pulley device (or gear device) to connect the motor and the steering shaft. The primary goal of controlling the steering wheel mechanism is to produce the steering feel and provide the road wheel reference angle signal.

7.1 BASIC CONTROLLER ALGORITHM

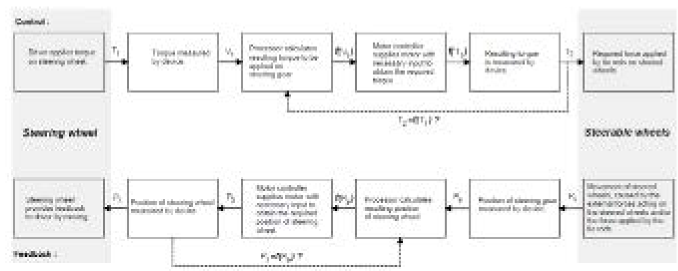

Fig Steer by wire Functional Block Diagram

The driver applies a torque T1 on the steering wheel (1). The steering wheel is firmly connected to the one-way working gear (4) and can therefore not be moved by the driver. The torque T1 applied by the driver is measured by the torque measuring device (2) and is represented by a voltage V1. The voltage V1 is transmitted to the processor (6) and a voltage f(V1) is applied by the processor (6) to the electrical motor (7). The voltage f(V1) is a function of the voltage V1 and can be dependant on defined rules concerning, for instance, vehicle speed and/or operator defined characteristics which is desired to influence the handling. By applying a voltage f(V1) to it the motor (7) will apply a torque T2 on the steering gear (8). The torque T2 is thus a function of the torque T1 applied on the steering wheel by the operator, T2= f(T1).

Obtaining the required output torque T2 from the motor (7) can be done by either relying on known characteristics of the motor so a given input gives a given output, or by refining the system by adding an additional torque measuring device (10) between the motor (7) and the steering gear (8). By adding an additional torque sensor (10) the voltage applied on the motor (7) can be fine-tuned to achieve the target value torque T2. Friction between the mechanical parts in the steering gear (8) and the tie rod steering connections (11) between the steering gear (8) and the controlled wheels (12), as well as the friction between the road surface and the controlled wheels (12), requires a torque T3 to be overcome. As long as the torque T2=f(T1)< T3 none of the parts move. If the torque T2 gets larger than the torque T3 the controlled wheels (12) start to move. The acceleration, and thus the speed by which the controlled wheels (12) begin to move, is determined by the resulting torque TResulting= T2- T3, being the difference between the torques T2 and T3. The motor (7) shall keep up and maintain the torque T2= f(T1) which means that the current to the motor must beincreased. This part of the system, the control part, is represented in the upper row in the information flow chart.

The position measuring device (9) measures the position P9 of the steering gear (8) and the position is represented electrically and constantly (or very frequently) transmitted to the processor (6). As long as the controlled wheels (12) do not move the readings from the position measuring device will not cause anything to happen. As soon as the controlled wheels (12) move the readings P9 of the position measuring device (9) change. The processor (6) will control the motor (5) in such a way that the position P3 of the steering wheel (1) as quickly as possible is made to correspond with the position P9 measured by the position measuring device (9) and thus P3=f(P9). The position P3 of the steering wheel (1) is measured by the position measuring device (3) It is evident that all signals between the units, both in the control part and in the feedback part of the system, can be represented as electrical voltages or currents or as digital values.. In an analogue system, voltages and currents are regulated continuously and controlled by operation amplifiers.In modern digitalised computer based systems the all-important motor controllers can operate with by fixed time intervals. By measuring the positions P3 of the steering wheel (1) and the position P9 of the steering gear (8) by fixed time intervals of Ät the processor (6) can determine a target value position P3Target of the steering wheel (1) for each timeframe of Ät. The processor (6) controls the motor (5) through a motor controller by adjusting the speed of the motor (5) so that the desired position P3Target of the steering wheel (1) can be obtained within a timeframe of Ät. If at the time Ät a position P91 of the steering gear (8) is measured by the position measuring device (9) and the position measuring device (3) measures a position P31=f(P91) of the steering wheel (1) no adjustment is required so the motor (5) does not move.At the time 2Ät the position measuring device (9) measures the position P92 of the steering gear (8) where the position P92 is different from the previously measured position P91 measured at the time Ät. This means that the steering gear (8), and thus the controlled wheels (12), has started to move. The position measuring device (3) is still measuring the position P31 of the steering wheel (1), since the operator can not move the steering wheel (1) due to the one-way working gear (4). The motor (5) shall then drive the steering wheel with a speed S1=(P32-P31)/Ät, where P32 is the desired position of the steering wheel determined by the processor (6) as P32=f(P92). At the time 3Ät the position measuring device (9) measures a position P93 of the steering gear (8) and a position P'32 (which is somewhere between P31 and P32) is measured by the position measuring device (3). Motor (5) now changes speed to S2=(P33- P'32)/Ät where P33 is the by now desired position of the steering wheel determined by the processor

(6) as P33=f(P93). If Ät is made adequately small it will in practical use appear as if the positions measured by the position measuring devices (3) and (9) change simultaneously. Using modern digital electronics frequencies of 100Hz or more should be achievable.

8 MODEL OFSTEER BY WIRE SYSTEM

8.1 SYSTEM IDENTIFICATION

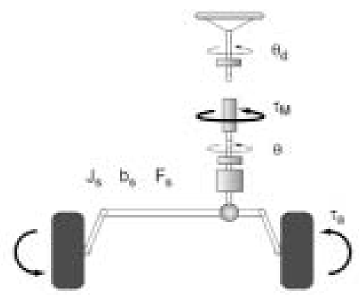

Fig .Steer by wire system dynamics

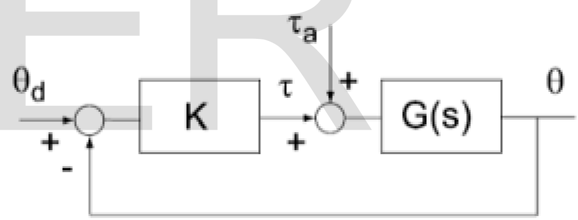

Fig. Closed loop system identification block diagram.

The closed loop transfer function of the system is as follows:

$$\frac{\theta(s)}{\theta_d(s)} = \frac{\omega_n^2}{S^2 + 2\xi\omega_{n^s} + \omega_n^2} = \frac{K}{J_s s^2 + b_s S + K}$$

ϴ - pinion angle

ϴd – commanded steering angle

Js – moment of inertia of the system

bs – effective viscous damping coefficient

K – feedback gain

ξ – damping ratio of the system

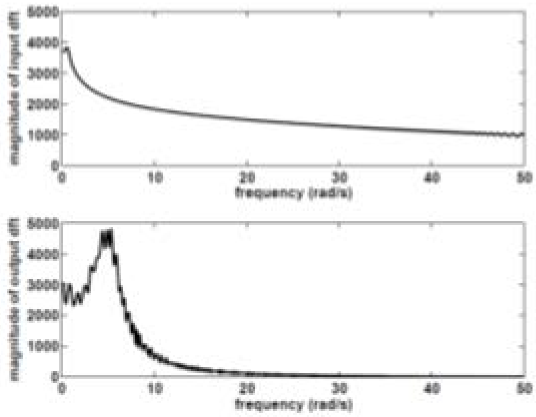

Fig Signals of Input and Output

$$\tau = J_s\ddot{\theta} + b_s\dot{\theta} + F_s sgn(\dot{\theta})$$

Fs – Coloumb friction coefficient

τ - actuator torque

8.2 FEEDBACK CONTROL

τ = τ feedback + τ feedforward + τ friction + τ aligning

$$\tau feedback = K_p(\theta_d - \theta) + K_d(\dot{\theta}_d - \dot{\theta})$$

Θd – desired steer angle

Kp – proportional feedback constant

Kd – derivative constant

$$\tau feedforward = J_s\ddot{\theta}_d + b_s\dot{\theta}_d$$

8.3 STEERING RATE AND ACCELERATION

First order filter :

$$\frac{\Theta_d(S)}{\Theta_d, sensor(S)} = \frac{\omega_c}{S + \omega_c}$$

Taking the inverse laplace:

$$\dot{\theta}_d = \omega_c(\theta_d, sensor - \theta_d)$$

Second order filter :

$$\frac{\Theta_d(s)}{\Theta_d, sensor(s)} = \frac{\omega_c^2}{S^2 + 2\omega_{c^8} + \omega_{c^2}}$$

Taking the inverse Laplace transform leads to a system of equations

$$\ddot{\theta}_d = \omega_c^2(\theta_d, sensor - \theta_d) - 2\omega_c\dot{\theta}_d$$

8.4 INTERNAL FRICTION OF STEERING SYSTEM

$$\tau friction = F_s sgn(\dot{\theta}_d)$$

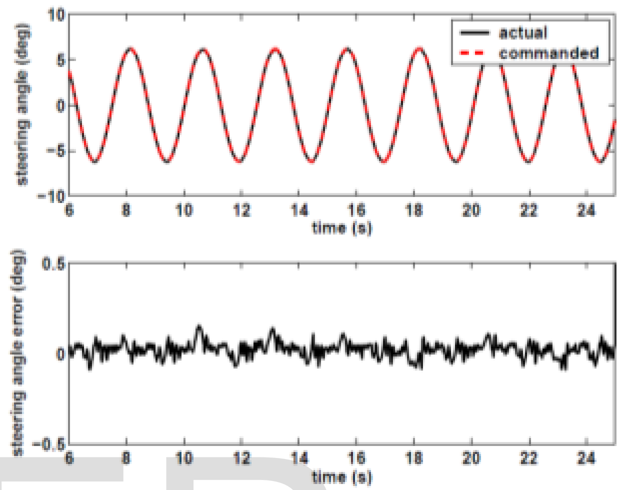

Fig. Feedback with feed forward and friction compensation

8.5 TIRE OPERATING SLIP ANGLE

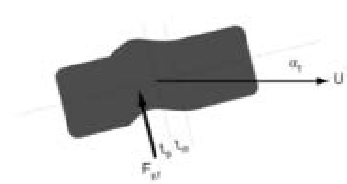

Fig slip angle

8.6 SELF-ALIGNMENT MOMENT

$$\tau_a = (t_p + t_m)F_{y,f}(\alpha_f)$$

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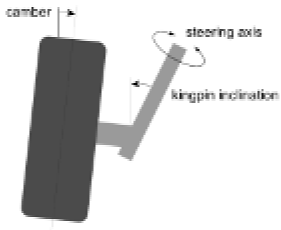

Fig Front axle geometry

8.7 ALIGNING MOMENT COMPENSATION

$$\tau\ \text{aligning} = k_a \hat{\tau}_a(\alpha_f)$$

Ka – scale factor to account for torque reduction by steering gear.

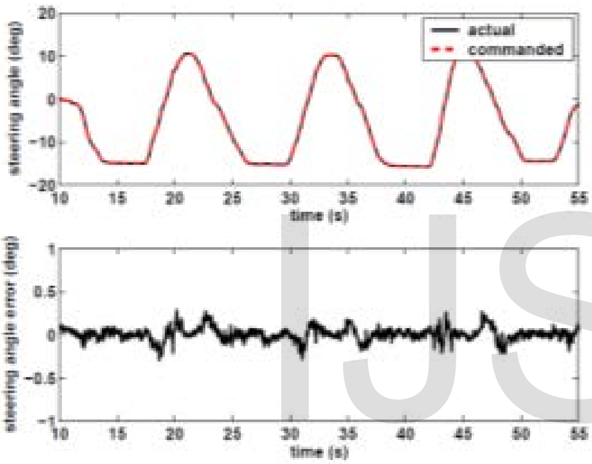

Fig Steering controller with alignment compensation

8.8 COMBINED CONTROL

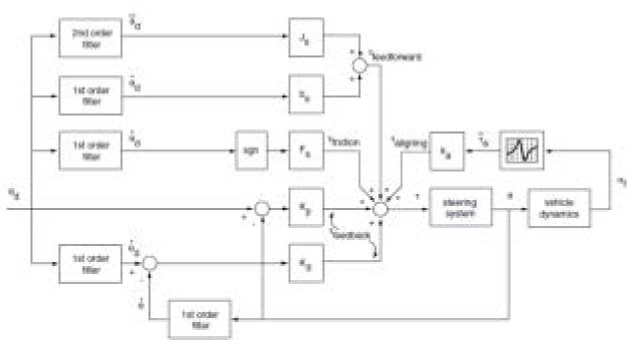

Fig Steering controller block diagram.

8.9 ERROR DYNAMICS

$$\ddot{e} = \frac{1}{J_s}(K_p e + K_d \dot{e}) + [F_s sgn(\dot{\theta}_d) - F_s sgn(\dot{\theta}) + k_a \hat{\tau}_a - k_a \tau_a]$$

$$= \frac{1}{J_s}(K_p e + K_d \dot{e}) + \delta e$$

8.10 ERROR

e = Θd – Θ

9 STEERING SYSTEM MODEL AT ROAD WHEELS

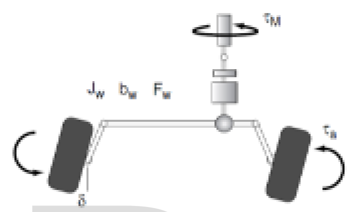

Fig steering system model

$$J_\omega \ddot{\delta} + b_\omega \dot{\delta} + \tau_f + \tau_a = \gamma_s \gamma_p \tau_M$$

Jω - Moment of inertia at road wheel

bω – damping at road wheel

τf – Coulomb friction

τa – tire self alignment torque

rs – steering ratio

rp – torque magnification factor

τM – steering actuator torque

10 TWO DEGREE OF FREEDOM BICYCLE MODEL

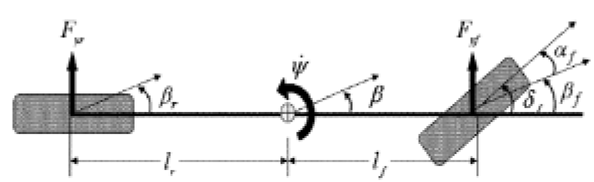

Fig Bicycle Model

$$K(deg/g) = \frac{1}{a_y}(\delta_f - 57.3\frac{L}{R})$$

K= 0 ; Neutral steer ($\alpha f = \alpha r$)

K>0 : Under steer ($\alpha f > \alpha r$)

K<0 ; Oversteer ($\alpha f < \alpha r$)

ay : vehicle's lateral acceleration

L : wheel base of the vehicle

R : Radius of vehicle cornering

δf : front wheel angle

11 RESULTS

LOCK TO LOCK ANGLE = 97 DEG

NO.OF TURNS FOR LOCK TO LOCK = 3.5 NOS

TIME TAKEN PER TURN = 2.5 SEC MIN

11.1 STEERING WHEEL VS ROAD WHEEL ANGLE

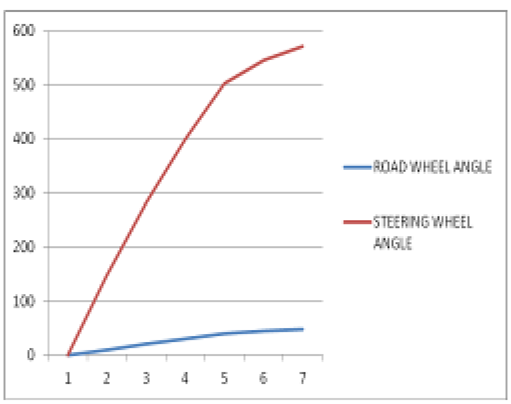

Fig Steering wheel Vs Road Wheel angle

For single side turn

13 CONCLUSION

Steer by wire has turned up as a great technology to be used in agricultural tractors for easy manufacturing and drive ability. In this phase of the project the torque requirements of the steering system and the control algorithm for the steering system is simulated. The major threat in case of agricultural tractor is the road to ground friction which varies drastically due to unpredictable operating conditions. The road wheel angles for the corresponding steering wheel angles are mathematically simulated and torque requirements are arrived.

In major critical operations like deep puddling the steering wheels are non functional and the direction control of the tractor is executed by differential braking of independent rear wheels. Steer by wire will be used in light duty operations like dry land preparation and haulage.

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